Are there non-strange low-lying penta-quarks and can we understand their width

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Abstract

We argue that the lightest isospin 1/2 partners of the $Z^+(1530)$ $\bar{s}uudd$ penta-quark predicted by Diakonov, Petrov and Polyakov are not the $N(1710)$ mixed anti-decuplet states, but the pure non-strange $\bar{u}(ud)(ud)$ and $\bar{d}(ud)(ud)$ penta-quark states which may lie as low as $1200\,MeV$. The expected low width of a few MeV of such a putative state may explain why it was missed in phase shift analyzes of pion-nucleon scattering.

Exotic tetra-, penta- and hexa-quarks have been discussed in the frame-work of QCD and various approximations thereof for more than three decades. The generally accepted point of view was that such states which certainly should exist are numerous, broad and hence blend in a continues background. The anomalous lightness of the Nambu-Goldstone pions allows most exotics to decay into a stable baryon and pions or just into pions with large phase spaces in all cases. It was also argued that decay rates of non exotics as $q\bar{q}$ mesons or qqq baryons requiring the creation of an extra and often even specific $q\bar{q}$ pair are suppressed [1] relative to the "fall-apart" decay of exotics like the $\Theta^+ \equiv \bar{s}uudd \to \bar{s}u + udd \equiv K^+n$, where all final quarks are already present in the initial state.

If pionic decays are partially blocked by the Zweig rule, suppressing $s\bar{s}$ annihilation into the

lighter $u\bar{u}$ or $d\bar{d}$ quarks, the relevant states like the $I = 0$ $f(980)$ and $I = 1$ $a(980)$, which following Jaffe [2] we take as $s\bar{s}q\bar{q}$ [1] configurations, can have reasonable $50 - 100\,MeV$ widths despite of the large phase space for pionic decays. It was then suggested that in certain heavier quark systems, such as the $\bar{c}suud$ penta-quark [3, 4, 5] or $ssuudd$ $\Lambda\Lambda$-hexa-quark [6] states, the favorable strong hyperfine interaction can generate stable multi-quark states which decay only weakly. It has been noted by several authors [7, 8, 9] that tetra-quarks, particularly the $cc\bar{q}\bar{q}$ or $c\bar{c}q\bar{q}$, are even more likely to be discovered. This was indeed verified in the Belle experiment [10], where a remarkable narrow peak was found in the $J/\Psi\pi^+\pi^-$ channel. This state which we believe has the quantum numbers of a $D^*\bar{D}$ in s-wave, namely $J^\pi = 1^+$, forms readily in the B decay involving two charm quarks in close spatial proximity and with reasonably low relative momenta. Its annihilation into J/Ψ and pions is still suppressed by the need to have the $c\bar{c}$ in the J/Ψ configuration causing its remarkable narrowness. This may be the first of a host of other $Q\bar{Q}q'\bar{q}$ exotica with $q', q \in \{u, d, s\}$. If the Babar $D_s(2317)$ state [11] is a $c\bar{s} \cdot (u\bar{u} + d\bar{d})/\sqrt{2}$ rather than p-wave $c\bar{s}$ state [12], QCD inequalities [13] suggest the existence of a third member in the series [14] starting with $f(980) \equiv s\bar{s}q\bar{q}$, namely the $I = 0$ $c\bar{c}q\bar{q}$ state with a mass $m \leq 3670\,MeV$ and a narrow width decaying into $\eta_c\eta$.

A $\bar{s}uudd$ penta-quark resonance at $m(\Theta^+) = 1540\,MeV$ has been seen in K^+n invariant mass distributions in various real photon experiments off deuterons [15, 16] and protons [17] by analyzing the K^-K^+n and $K_s^0K^+n$ final states without being swamped by multiple pion complex final states. This resonance has also been reported in K^+-Xenon scattering [18] and the possible existence of a very weak evidence in K^+d cross section data in the PDG (Particle Data Group compilation) [19] was noted [20].

The most remarkable feature of the new state is the narrow width $\Gamma_{\Theta^+} < 25\,MeV$ seen in γd and γp experiments where this upper bound is given by the experimental resolution. A much more stringent bound of $\Gamma < 3 - 6\,MeV$ [20] follows from the lack of a prominent

[1] q refers to the lightest quarks (u, d), Q to heavy quarks (c, b) and the intermediate s is mentioned explicitly.

enhancement of the K^+d scattering cross section in the relevant K^+d momentum interval whose size is fixed by the Fermi motion in the deuteron. An even stronger upper bound of $\Gamma < 1\, MeV$ is derived from a phase shift analysis [21] and by analyzing along similar lines the K^+ charge exchange reaction [22].

Motivated by this new development we would like to suggest schemes where the width can be as small as $\Gamma < 1 - 3\, MeV$ and to dispel the belief that, when decays into pseudo scalar particles are allowed and the Zweig rule does not apply, the exotics are always extremely broad. Thus a very different explanation why multi-quark exotics have not been seen before emerges. Their widths are no longer too large but too small, causing the production cross sections for these exotic states scaled by their widths Γ to be so tiny that the peaks in the invariant mass distribution escaped detection in earlier lower statistics and/or lower resolution experiments.

A $Z^+(1530)$ state with a width of $5 - 15\, MeV$, $I = 0$ and $J^\pi = \frac{1}{2}^+$ has been predicted in an extended SU(3)-flavor Skyrme model [23, 24]. It appears as the isospin singlet tip of an anti-decuplet where the corresponding $I = \frac{1}{2}$ doublet has been identified with the $N(1710)$ $J^\pi = \frac{1}{2}^+$ state. Diakonov, Petrov and Polyakov also suggest that the $\Sigma(1890)$ and $\Xi(2070)$ states are the remaining penta-quark states of this anti-decuplet, leaving only the Z^+ to be discovered.

With the $Z^+(1530)$ and the corresponding measured $\Theta^+(1540)$ at hand we should anchor the penta-quark scale at $1540\, MeV$ and look for other even lighter penta-quark states comprising u, d and s quarks and anti-quarks.

In the anti-decuplet the $S = 0$ $N(1710)$ is obtained from the Z^+ by the U spin lowering operator, that replaces in $Z^+ \equiv \bar{s}uudd$ either one d by a s or one $\bar{s}$ by a $\bar{d}$, yielding

$$|N\,,\, I = \frac{1}{2}\,,\, I_z = -\frac{1}{2} >= \sqrt{\frac{1}{3}}|\bar{d}uudd > + \sqrt{\frac{2}{3}}|\bar{s}uuds > . \qquad (1)$$

The matrix element of the SU(3) breaking Lagrangian $m_s\bar{\Psi}_s\Psi_s - m_d\bar{\Psi}_d\Psi_d$ in the $N(1710)$ state is $\frac{4}{3}\Delta_m^{penta}$ and Δ_m^{penta} in the case of $Z^+(1530)$. Δ_m^{penta} is an effective s and d quark mass difference which subsumes also the hyperfine mass splitting effects. The mass dif-

ferences between these $I = 0$ and $I = \frac{1}{2}$ penta-quark states is then

$$m(N(1710)) - m(Z^+(1530)) = \frac{4}{3}\Delta_m^{penta} - \Delta_m^{penta} = \frac{1}{3}\Delta_m^{penta} = 180\,MeV. \qquad (2)$$

This large effective strange versus up or down quark mass difference in the penta-quark system $\Delta_m^{penta} = 540\,MeV$ is more than three times larger than the difference in the standard baryonic decuplet $\Delta_m^{baryon} = 160\,MeV$ that is traditionally identified with the constituent mass difference between the strange s and non-strange u, d quarks. As we indicate next a large $\Delta_m^{penta} = 200 - 400\,MeV$ could be a better prediction reflecting the large hyperfine splittings in case of the $q_i\bar{q}_j$ Nambu-Goldstone pions associated with the spontaneous chiral symmetry breaking which the Skyrme model incorporates.
General arguments based on QCD inequalities motivate

$$\Delta_m^x = m(X\bar{s}) - m(X\bar{q}) > m_s^c - m_q^c = \Delta_m^c. \qquad (3)$$

This conjecture constituting a stronger variant of Vaffa-Witten's rigorous result [25] will be addressed separately in detail. The masses on the left are those of the lowest lying states with given J^π consisting of the same subsystem X with an extra $\bar{s}$ or $\bar{q}$ quark in the same overall state and $m_{q,s}^c$ are the current quark masses. Δ_m^c is smaller than the standard Δ_m^{baryon} of $160\,MeV$ in common quark models. It has been noted [26, 27] that $\Delta_m = m(Q\bar{s}) - m(Q\bar{q})$ monotonically decreases with m_Q. This is expected from the $1/m_Q$ decrease of the attractive hyperfine interaction.

$$< \Psi_H|\mathcal{L}_{hfi}|\Psi_H >= \sum_{i,j} C_{i,j}(H) \cdot \frac{(\vec{\sigma}_i \cdot \vec{\sigma}_j)(\vec{\lambda}_i \cdot \vec{\lambda}_j)}{m_{q_i} \cdot m_{q_j}} \qquad (4)$$

The sum extends over all the quarks and anti-quarks in the hadron H and $C_{i,j}(H)$ is the relative wave-functions at zero separation of the various q_iq_j or $q_i\bar{q}_j$ pairs in the hadron H. The components of $\vec{\sigma}$ are the 2×2 Pauli matrices σ_α with $\alpha \in \{1...3\}$ and those of $\vec{\lambda}$ are the 3×3 Gelman matrices λ_β with $\beta \in \{1...8\}$ representing the eight SU(3) color generators in the **3** and $\bar{\mathbf{3}}$ basis of quarks and anti-quarks. For pseudo-scalar hadrons this differences $\Delta_m = m(Q\bar{s}) - m(Q\bar{q})$ starting for light quarks with

$m(K) - m(\pi) \approx 360\,MeV$ decrease all the way down to $m(B_s) - m(B_u) \approx 90\,MeV$ for b quarks. Nussinov and Shrock have conjectured [26] that indeed the latter mass difference more correctly represents the current quark mass difference Δ_m^c in agreement with lattice results [28]. One has to correct for running quark masses [29] since, due to the increased reduced mass, the $Q\bar{q}$ state is smaller than the corresponding $q\bar{q}$ state. The empirical strange non-strange Δ_m^{baryon} values of $150 - 250\,MeV$ can now be explained by this smaller Δ_m^c and hyperfine interactions using constituent quark masses similar to those in the mesons and the fact that the hyperfine splitting in baryons is reduced relative to that in mesons due to $< baryon|\vec{\lambda}_i \cdot \vec{\lambda}_j|baryon >= 1/2 < meson|\vec{\lambda}_i \cdot \vec{\bar{\lambda}}_j|meson >$.

Next we would like to identify the likely non-strange analogue of the $\Theta^+(1540)$ penta-quark and estimate in the same manner Δ_m^{penta}.

In many multiplets like the vector and tensor meson nonets the physical mass eigenstates are adequately represented by the $I = 0$ non-strange $|(u\bar{u} + d\bar{d})/\sqrt{2} >$ and strange $|s\bar{s} >$ quark states and are far from the SU(3) flavor singlet $|(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3} >$ and $|(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6} >$ octet state. This is due to the fact, manifested in the Zweig rule, that the $s\bar{s} \rightleftharpoons gluons \rightleftharpoons u\bar{u}$ off diagonal matrix elements are smaller than the mass difference between the two strange and two non-strange (u or d) quarks.

An important exception to this are the mesons π, K, η and η' of the pseudo-scalar octet with a strong coupling to the pure glue channel, often attributed to the U(1) axial anomaly. The Skyrme model contains the U(1) axial anomaly and the Skyrmions can be viewed as a coherent π, K, η fields. Hence the emergence in first order of the SU(3) symmetric anti-decuplet of Diakonov, Petrov and Polyakov can be understood [30]. Note however that a detailed analysis of the radiative widths [31] suggests that also the η and η' are intermediate states between the mixed and pure SU(3) flavor states.

We explore the possibility that the lowest lying partners of the $\Theta^+(1540)$ are essentially the pure non-strange $\bar{u}(ud)(ud)$ and $\bar{d}(ud)(ud)$ penta-quark states P^0 and P^+.

In the penta-quark state we encounter for the first time two di-quarks taken in the simplest

model [32, 20] to be the standard strongly bound $I = 0 \;\; S = 0$ $(u_1 d_1)$ and $(u_2 d_2)$ with an relative angular momentum $L_{12} = 1$. The task of estimating the difference between the analog states $m(\Theta^+) - m(P)$ where P is obtained by exchanging $\bar{s}$ in $\Theta^+ \equiv \bar{s}(u_1 d_1)(u_2 d_2)$ by $\bar{u}$ or $\bar{d}$ seems easier,

$$m(\Theta^+) - m(P) = \Delta_m^c - \sum_{q\in\{u,d\},i\in\{1,2\}} C_{\bar{s},q_i} \cdot \frac{(\vec{\sigma}\cdot\vec{\sigma}_i)(\vec{\bar{\lambda}}\cdot\vec{\lambda}_i)}{m_s \cdot m_q} + \sum_{q\in\{u,d\},i\in\{1,2\}} C_{\bar{q},q_i} \cdot \frac{(\vec{\sigma}\cdot\vec{\sigma}_i)(\vec{\bar{\lambda}}\cdot\vec{\lambda}_i)}{m_q^2} \quad (5)$$

where we sum only over the hyperfine interactions between the anti-quark and the four quarks in the penta-quark state because the remaining mutual $q_i q_j$ interactions cancels out. Since each of the di-quarks $u_i d_i$ has $S = 0$ the expectation value of each of the four hyperfine interactions vanishes. In this lowest order approximation we thus find $m(\Theta^+) - m(P) \approx \Delta_m^c \approx 100\,MeV$. But this result has to be questioned because the penta-quark state with two rigid $I = 0 \;\; S = 0$ ud di-quarks is only justified if the remaining anti-quark is a heavy c or b quark with small mutual $\bar{Q}q_i$ hyperfine interactions. This is no longer the case when the anti-quark is a $\bar{u}$ or $\bar{d}$ because lower energies are obtainable if a $S = 1$ admixture in the di-quark is allowed while benefiting from the very large $\bar{q}q$ hyperfine interaction with $S_{\bar{q}q} = 0$. The scale for the strength of this hyperfine interaction is set by $m(K_{\bar{s}q}) - m(\pi_{\bar{q}q}) \approx 360\,MeV$. This as well as the large mass splitting in the Diakonov, Petrov and Polyakov anti-decuplet widens the likely $m(\Theta^+) - m(P)$ range from $100\,MeV$ up to $350\,MeV$.

Such a non-strange penta-quark P, with a mass of $1200 - 1450\,MeV$ and $I = 1/2$ could be seen in $\pi^- p$ but not in $\pi^+ p$ system. A new resonance cannot be ruled out by $\pi^- p$ phase shift analyzes, if the resonance is as narrow as $\Gamma < 5\,MeV$ and its cross section small [2]. The full circle in the Argand diagram is completed within an interval $\Delta_W \approx 2\Gamma$ requiring a high energy resolution and a small step width of less than $0.5\,MeV$ to measure the Argand diagram, not taking into account that even in $0.5\,MeV$ W bins the total P to $\pi^- p$ cross section ratio is only $0.1 - 0.3$. In one of the few high resolution experiments

[2] The total formation cross section at the maximum of the P resonance in the $\pi^- p$ channel of $5 - 25\,mb$ is smaller than the one in the $K^+ n$ channel at $W(m_{\Theta^+})$ of 37 mb [20].

narrow peaks in $\pi^- p$ channel have indeed been seen in the reaction $^{12}C(e, e' p \pi^-)^{11}C$ at MAMI [33]. The high missing mass resolution of $\sigma_m = 0.27\,MeV$ allows to identify two $4\,MeV$ narrow states at an invariant mass of $1222\,MeV$ and $1236\,MeV$ that have been interpreted as bound Δ^0 states. Interestingly a narrow resonance with a mass of $1225\,MeV$ and a width of $50\,keV$ was found to diminish the χ^2 of partial wave analyzes based on the πN SAID data base [34].

The most puzzling aspect of the $\Theta^+(1540)$ is the narrow width $\Gamma < \mathcal{O}(1-3\,MeV)$ established by K^+ nuclear scattering data. If the $\Theta^+(1540)$ will survive further experimental scrutiny and even more so if lighter narrow analogues exist, then finding a credible scenario for such narrow widths is a challenge to QCD, which should at least qualitatively explain all hadronic data. The penta- and tetra-quark are more complex than ordinary baryons and mesons. In a chromoelectric flux tube model (CFTM) mesons are tubes with the radius b of chromoelectric flux extending between the quark and anti-quark at both ends. It generates a confining linear potential $V = \sigma \cdot r_{q\bar{q}}$ where σ is the string tension [35, 36]. This picture is particularly appropriate for states with large angular momenta and length $r_{q\bar{q}} = a \gg b$. In this limit linear Regge trajectories with a slope $\alpha' = 2\pi\sigma \approx 1\,GeV^2$ arise and in the limit of $b \to 0$ a string like model emerges.

In the CFTM baryons consist of three flux tubes which join at a junction J. The tetra- and penta-quarks have more elaborate color networks with two and three junctions respectively (see Fig.1). The complexity of the penta-quark state suppresses its formation in hadronic collisions due to the specific rearrangements that are required. By detailed balance the system will then also be trapped for a long time while finding the specific path back to the original hadrons. The CFTM offers a concrete realization of this general concept. To allow for the penta-quark state to decay into baryon and meson or for the tetra-quark state to decay into two mesons a junction J and the anti-junction $\bar{J}$ have to annihilate before the flux tubes can reconnect to generate the final two hadrons. A necessary but not sufficient condition for the annihilation is that J and $\bar{J}$ are within a relative

distance smaller than the flux tube radius b. In a simplistic terta-quark model we identify the centers of mass of the di-quarks $q_1 q_2$ and $\bar{q}'_1 \bar{q}'_2$ with the junctions J and $\bar{J}$. These junctions are treated as scalar particles with the mass of the di-quarks $m_{dq} \approx 650\, MeV$. These particles are in the color representation $\bar{\mathbf{3}}$ and $\mathbf{3}$ with the same linear potential as between the quarks in a meson. The two junctions are in a relative p-wave. Let $< r_{J\bar{J}} >$ in the lowest state be a. Since the $l = 1$ wave-function decreases linearly in the small r region, the probability $P(r < b)$ is approximately $(b/a)^5$. For $\sigma \approx 0.15\, GeV^2$ we estimate, using the minimum of the radial potential and the curvature d^2V/dr^2 at this minimum, that $r_{min} \approx <r> \approx a$ is larger than $0.7\, fm$. For b in the range of $0.2 - 0.5\, fm$ the

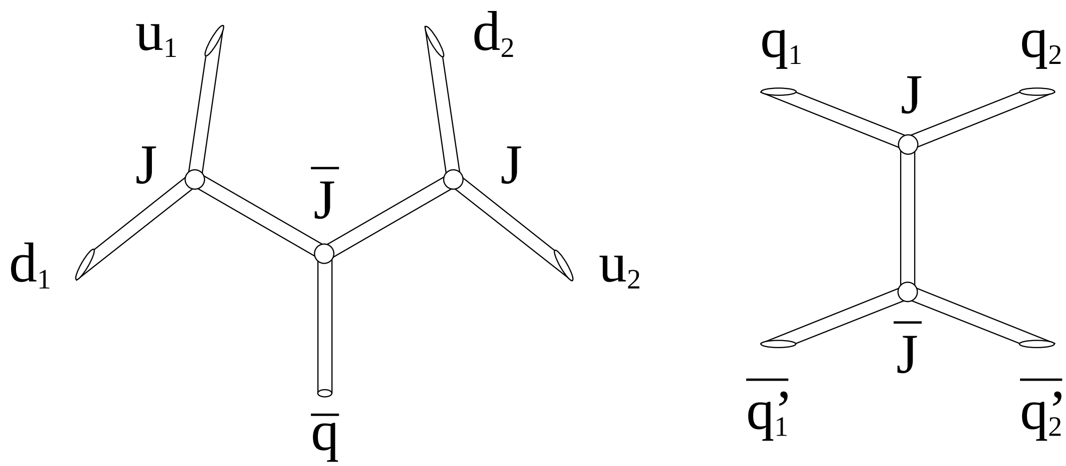

Figure 1: Schematic description of the net-works of the chromoelectric flux tubes in case of the tetra-quark (right) with one junction J and one anti-junction $\bar{J}$ and the penta-quark (left) with two junctions and one anti-junction. Three fluxes belonging in the fundamental $\mathbf{3}$ color representation are flowing into a junction J and three such fluxes are flowing out of an anti-junction $\bar{J}$. Any outgoing/incoming flux in color $\mathbf{3}$ is equivalent to an outgoing/incoming flux in color $\bar{\mathbf{3}}$ representation. The fluxes are locally coupled to a singlet via $\varepsilon_{abc}\Phi_a\Phi_b\Phi_c$ with a, b, c the three colors. The drawing shows an idealized case where the length a of the flux tubes joining J and $\bar{J}$ are significantly larger than the radius b of tube.

probability $P(r < b)$ is smaller than $0.002 - 0.2$.

To estimate the decay rate note that the relative coordinate r changes by $2a$ during a period T exceeding $a/c \approx 0.7\, fm/c \approx (300\, MeV)^{-1}$. During each period $J\bar{J}$ annihilation occures with a probability which is smaller than $P(r < b)$. Hence the decay rate is $\Gamma^{Tetra} < P(r < b) \cdot 300\, MeV = 0.6 - 60\, MeV$. In the penta-quark either of the two junctions J (see Fig.1) can annihilate with $\bar{J}$, therefore we expect roughly twice this width.

The crucial flux tube radius b can be determined by pure gluo-dynamics up to small $1/N_c^2$ corrections. The large mass of the lightest glue-ball is expected to be above $m_{gb} \geq 1.6\, GeV$. This sets the scale for the radius of the flux tube to $b = 1/m_{gb} \leq 0.15\, fm$. A full QCD lattice simulation, recently performed for QQQ baryons with three quarks pinned down at relative distances of $r_{qq} \approx 0.7\, fm$, clearly reproduces the Y shape of the flux structure shown in an action density contour plot [37]. The corresponding flux junction radius is $b \leq 0.2\, fm$. Even in the ground state qqq nucleons, where the light quarks move so fast that the short flux tubes get tangled up into a more uniform spherical distribution than in the case of the $\bar{q}(ud)(ud)$ penta-quark states, the flux junction radius will remain the same.

On the other hand the distance a between J and $\bar{J}$ in tetra-quarks is related to the distance between the quark and anti-quark in mesons, because both have the same color charges and the same flux tubes. In mesons a is essentially the charge radius of the pion $r_\pi \approx 0.65\, fm$. The di-quark masses are $m_{dq} = 650\, MeV$ instead of $350\, MeV$ for the light quarks. For a linear potential this scales the size by $(m_q/m_{dq})^{\frac{1}{3}}$. However here, the two di-quarks are in a p-wave. The resulting additional centrifugal barrier effectively doubles the kinetic energy reducing the mass by a factor of about 2, which restores $< r_{J\bar{J}} >= a$ back to out initial estimate of about $0.7\, fm$.

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